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SIGNAL PROCESSING, SIMULATION, AND COMMUNICATIONS STUDY

(First Quarterly Technical Report)

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DEPUTY FOR ADVANCED PLANNING
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LASA SIGNAL PROCESSING,

SIMULATION, AND COMMUNICATIONS STUDY

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SYNOPSIS

This is the first Quarterly Technical Report under Contract No. AF 19(628)-5948 and it sets forth a functional description of a LASA Signal Processing System. The system parameters have been chosen by taking advantage of important system tradeoffs to reduce the hardware necessary to implement the known operating requirements. The system discussed herein is configured to allow considerable experimentation. Generalized processing techniques and system partitioning have been employed to permit growth and change on the basis of experimental results. On the other hand, certain desired operational system functions and performance objectives can at this time be identified. These have been taken into account so that immediate advantage can be taken of existing array equipments and signal processing technology.

In Section 1, the system objectives are presented in terms of tradeoffs to establish surveillance requirements. Sections 2 and 3 contain a function and data flow description to establish methodology and technique, respectively. Section 4 presents operational and maintenance considerations with respect to system operation and system partitioning. Certain pertinent topics related to signal processing specifications and system tradeoffs and requirements are presented in Appendices A, B, C, and D. The method of calculating optimum filter coefficients is described in Appendix E.

CONTENTS

ILLUSTRATIONS

Section 1

SYSTEM OBJECTIVES

The purpose of the LASA Signal Processing System is to provide surveillance at teleseismic distances on a world-wide basis. The processing can be divided into two functions:

a. Detection processing—determines the existence of a potential event; must be carried out continuously and in real time.

b. Event processing—determines the event location, onset, and waveform; performed off-line provided reasonable limits on the backlog of unprocessed detected events are maintained.

In this section, the operational parameters are discussed and related to the processing requirements in terms of the number of pre-formed beams to be generated. The results obtained can be used when analyzing required signal processing equipment capability.

1.1 OPERATIONAL PARAMETERS

The following parameters can be employed to describe the operational requirements:

Surveillance region

Quality of event detection

Quality of event processing

1.1.1 Surveillance Region

Three surveillance regions have been considered:

a. World-wide

b. Land masses and seismic zones

c. Land masses

In each case, surveillance only at teleseismic distances is intended.

The surveillance region can be most conveniently displayed in the "inverse-velocity" plane, where the coordinates (u_x, u_y) are the reciprocals of the horizontal phase speed components of a seismic wave front at the LASA site. In terms of this representation, teleseismic event locations lie at distances between 0.04 sec/km and 0.08 sec/km from the origin $(u_x = u_y = 0)$. Figure 1-1 depicts the surveillance region considered.

1.1.2 Quality of Detection Processing

The detection function will be performed by means of a two-step beam-forming process. Since only a limited number of pre-formed beams can be generated, some amount of processing loss will be unavoidable. This loss, which is largely dependent on the beam density, will be termed the "beam coverage loss" and has been specified as follows:

For subarray beams— maximum loss of 1.3 dB at 1.5 Hz

For LASA beams—maximum loss of 1.7 dB at 1.5 Hz

This allows a maximum beam coverage loss of 3dB at 1.5 Hz. The choice of 1.5 Hz has been based on the assumption that the input signal-to-noise ratio tends to peak at or below 1.5 Hz, so that the frequency region at or below 1.5 Hz is most suitable for detection processing.

In addition to the beam coverage loss there will also be a processing loss when the detection LASA beams are formed from fewer than 21 subarray beams. This additional loss (in terms of dB) has been depicted in Figure 1-2 as a function of SA, the number of subarray beams used.

1.1.3 Quality of Event Processing

Here the emphasis is on accuracy of event location and time of onset, as well as on fidelity of the event waveform processing. Therefore, the high-frequency contents of the signal must be preserved as much as is feasible. For this reason, the allowable beam-coverage loss for event beams has been specified as 3dB at 3Hz. This loss is reserved entirely for the event LASA beams, since the subarray beam will be directed along the centerline of the detection LASA beam containing the event.

INVERSE VELOCITY—SPACE MAP of the WORLD

SUBARRAY BEAM
1.3 dB at 1.5 Hz
D = 0.080 sec/km

0.08

ALASKA

GREENLAND

U.S.S.R

CHINA

SPAIN

AFRICA

MIDWAY IS.

0.04

sec/km

HAWAII

SAMOA

SOUTH AMERICA

0.04

1.5 Hz
DETECTION BEAM
9 dB CONTOURS:
— 13 SA (FILLED BY 153 EB)
— 17 SA (FILLED BY 102 EB)
— 21 SA (FILLED BY 59 EB)

D = 0.0024 sec/km

EVENT BEAMS 3dB at 3 Hz

MEXICO

0.08

sec/km

DETECTION BEAMS

3.0 dB at 1.5 Hz,
including 1.3 dB
SA beam loss.

21 SA: D= 0.0035 sec/km
17 SA: D = 0.0061 sec/km
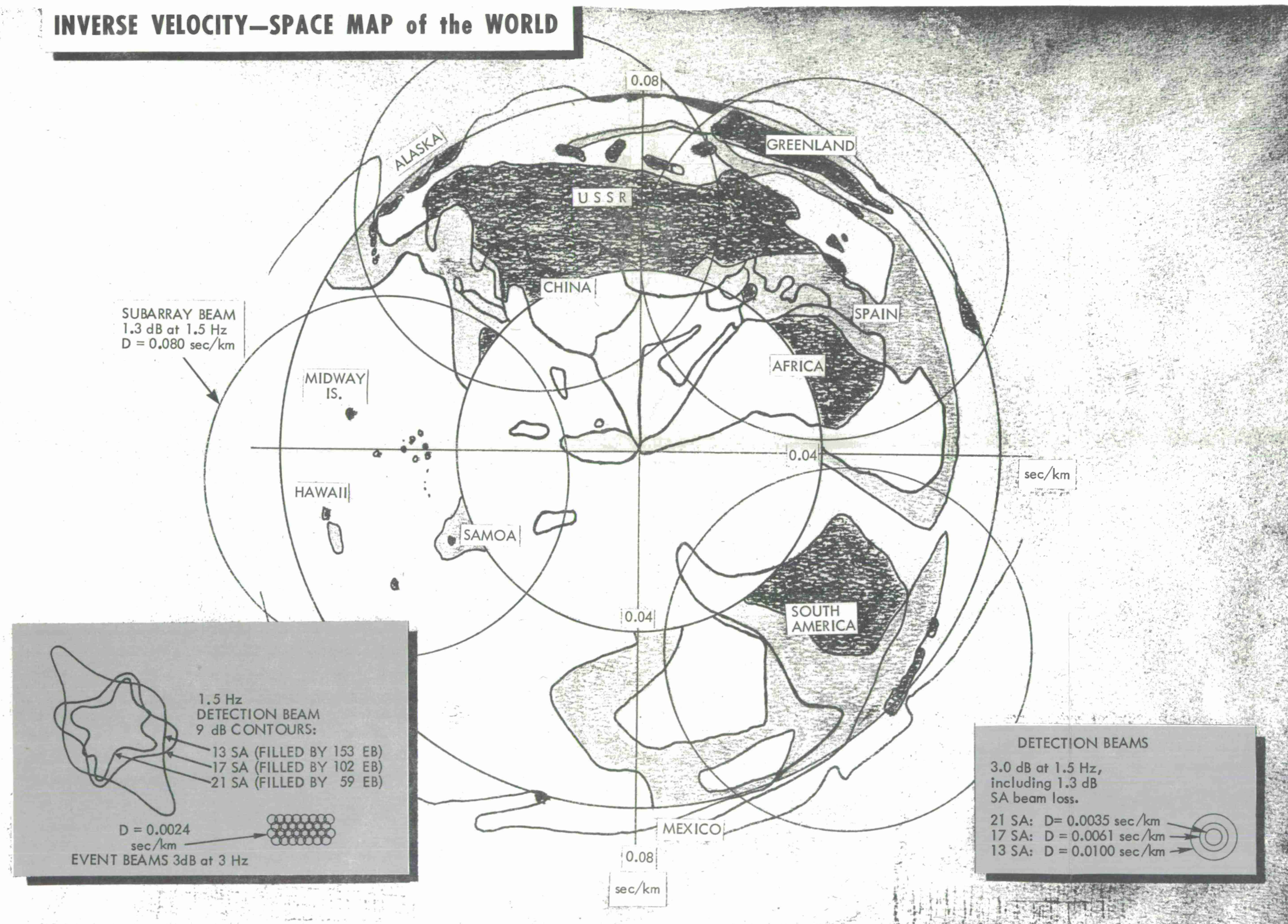13 SA: D = 0.0100 sec/km

Figure 1-1. Inverse Velocity—Space Map
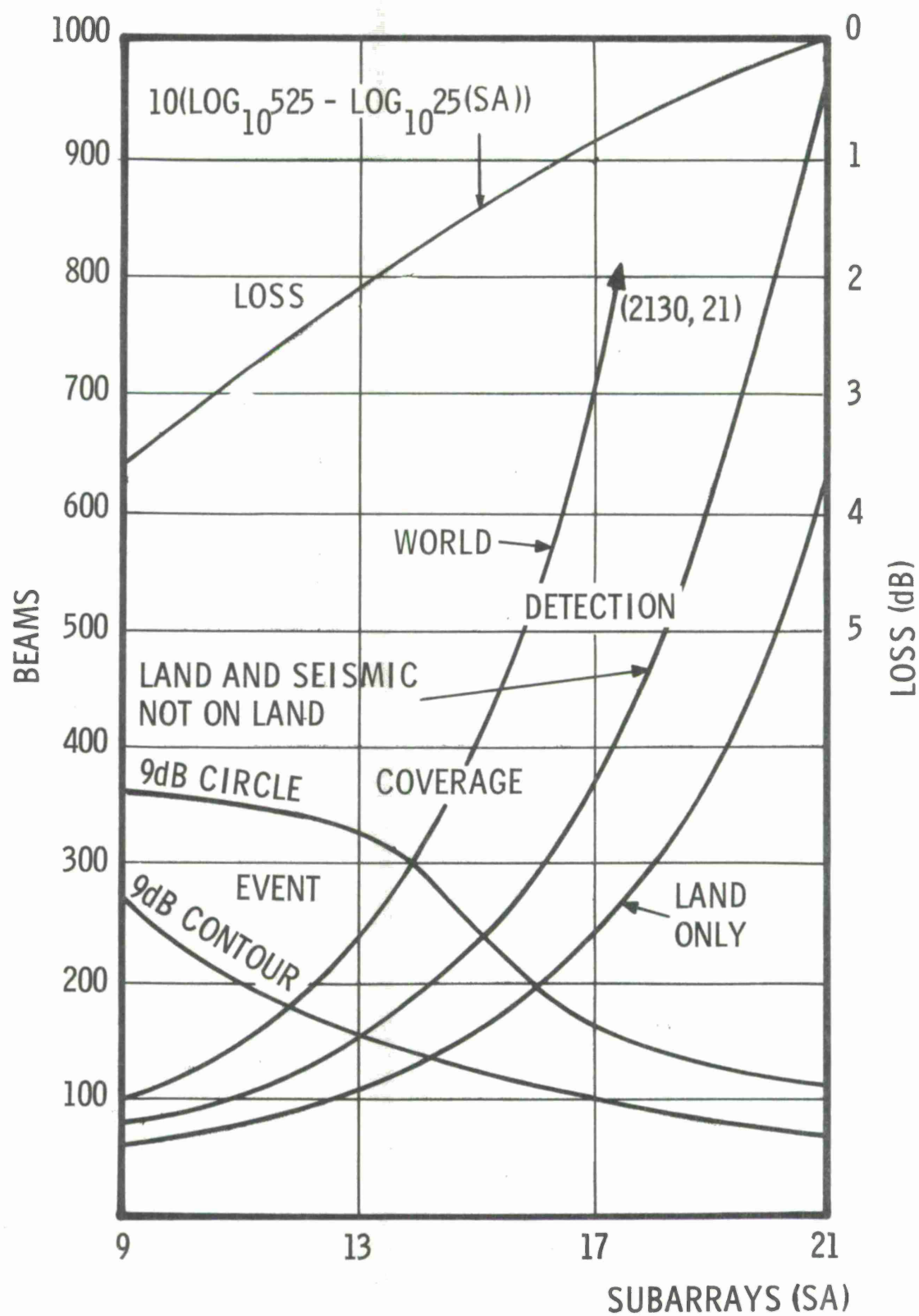of the World

Figure 1-2. Beam Surveillance Coverage

The region to be covered must be the region of uncertainty for the event to be processed. Therefore, the region to be covered is chosen to be centered on the detection LASA beam containing the event. So far as its boundary is concerned, two cases have been considered: (1) the case where the region is bounded by the detection LASA beam's 9.0 dB contour at 1.5 Hz, and (2) the case where the region is the smallest circle containing the 9.0 dB contour.

1.2 BEAM FORMING REQUIREMENTS

Here, the number of subarray beams per subarray, and the number of LASA beams to be formed for the detection function is discussed. Likewise, the number of event LASA beams is considered. In arriving at these numbers, conventional beam forming has been assumed. For additional details, the reader is referred to Appendix A as well as to the IBM Final Report: "Large-Aperture Seismic Array Signal Processing Study," Contract No. SD-296, 15 July 1965.

1.2.1 Detection Beams

The number of subarray beams to be formed per subarray ranges from six (for world-wide surveillance) to three (for continental land masses only). Intermediate values are required when Pacific Islands or seismic zones are to be included.

The number of detection LASA beams to be formed depends not only on which of the three surveillance regions (as defined in paragraph 1.1.1) is to be covered, but also on the number of subarrays included in the LASA beam forming process. Choosing the subarrays (SA) as near the LASA center as possible, the detection LASA beam broadens and the number of such beams decreases as SA decreases. The graphs of the number of detection LASA beams as a function of SA are shown in Figure 1-2 for each of the three surveillance regions.

It is emphasized that taking SA less than the total number of 21 subarrays will cause a performance loss in addition to the 3.0 dB beam coverage loss. This additional loss (in terms of dB) is shown in Figure 1-2 as a function of SA.

1.2.2 Event Beams

Here only one subarray beam is formed per subarray, employing either conventional or optimum beam forming. In Figure 1-2, the number of event LASA beams was shown as a function of the number of subarrays included in the detection LASA beam forming process. Two curves are displayed, corresponding to the two regions of coverage as defined in paragraph 1.1.3. It is intended that for event LASA beams, all subarrays will be used for event processing.

1.3 COVERAGE VARIABILITY CONSIDERATIONS

In the above analyses, it can be shown that the number of beams required per unit area is highly sensitive to changes in the assumed value of the detection processing frequency (see Appendix B). From such an analysis, it can be concluded that only through careful and extensive experiment can the beam requirements be more precisely contained.

Further, the above considerations are aimed at obtaining sufficient beam coverage for the direct and surface-reflected teleseismic P-wave arrivals. It may be necessary, however, to consider additional beam requirements to also process shear waves and perhaps some of the core reflected modes. This requirement is expected to pose no signal processing difficulty in event processing, where its application appears most important. For detection processing, it appears desirable to have sufficient spare detection beam coverage available to test detection techniques for shear wave and core reflected phases.

Section 2

SYSTEM FUNCTIONAL REQUIREMENTS

The LASA Functional System Diagram is shown in Figure 2-1. The seis-
mometers, subarrays, and multiplexer perform the system data acquisition
function. System functions are divided among three computers. Machine
number 1 is called the Detection Processor and receives its inputs in real time
to determine if the incoming data contains an event. It performs the functions
of beam forming, filtering, rectifying, integrating, and thresholding. Machine
number 2 is called the Event Processor. In addition to signal processing func-
tions similar to those in the Detection Processor, this machine controls the I/O
equipment associated with the system. Its prime function is to generate the
best record that can be made of the event. Machine number 3 is the Auxiliary
Processor and is used to calculate optimum processing filter coefficients and
for scientific computations.

Should equipment failure require it, the Event Processor is capable of
substituting for the Detection Processor. Under this condition, a backlog of
event tapes is generated. The Event Processor must have adequate capacity to
reduce this backlog when it returns to event processing.

The Detection Processor, Event Processor, and I/O devices are discussed
in more detail in this section. Auxiliary Processor functions are detailed in
Section 3.

2.1 SYSTEM INPUTS

The system inputs are:

      25 seismometers from each of 21 subarrays

      Each seismometer is sampled at 10 Hz

      Each seismometer, except one per subarray, is quantized at
      0.028 nm/bit

Figure 2-1. Functional System Diagram

The exceptional seismometer is quantized at nominally 0.028×2^7 nm/bit

Each seismometer word length is 14 bits (13 data plus sign).

A tolerance analysis on seismometer sensitivity, phasing, and processor scaling is presented in Appendix C.

2.2 SYSTEM OUTPUTS

The system outputs are considered in two parts. Although the Detection Processor performs an intermediate function and provides the input to the Event Processor, its output may be considered as a system output. However, the outputs of the Event Processor generally constitute the system outputs.

2.2.1 Detection Processor Outputs

The Detection Processor outputs are:

Seismometer tapes

A detection alarm

Event tapes

All incoming data is stored on seismometer tapes that are retained for a fixed time period (suggested to be 10 days). After this time the tapes are re-cycled on the assumption that any event of interest has been detected and pro-cessed from them.

Provision is made for adjusting the detection threshold as an input control to the Detection Processor. When the detection threshold is exceeded and the event criteria fulfilled, a detection alarm will alert the operator and the detection will be recorded in the system log. Upon event detection an event tape is generated that contains a record of all seismometers for a period prior to the event and continuing through the duration of the event. The event tape record length required for optimum processing is discussed in Appendix D.

2.2.2 Event Processor Outputs

The Event Processor outputs are:
An event record tape
An event display
An event trace
A seismic bulletin
A system log

The output of the Event Processor is a large number of beams clustered around the indicated location of the event. These beams differ from the detection beams only in the degree of sophistication employed in the signal processing to obtain a greater beam gain and frequency response. A problem exists in selecting the best beam from among these beam outputs to provide the permanent record of the event, called the event record tape. Although automatic selection of the beam for the event record tape appears feasible, initially, selection may depend upon the visual comparison of beam magnitude plotted as a function of time. When current studies enable firm specifications to be developed, a cathode ray tube display may be suggested as an interim solution to this problem. Such a display, positioning the beams relative to their inverse velocity space location, and modulating intensity with beam magnitude, may allow the operator to select the beam for the event record tape. If automatic selection is proven feasible, the display can be relegated to the function of aiding the operator in monitoring the system.

The event trace is a plot of the event record tape produced on the digital plotter and becomes a permanent record of the event. Other permanent records of the event are the seismic bulletin and system log which are discussed in more detail below.

2.2.2.1 Seismic Bulletin

The calculated values of interest include the time, magnitude, duration of the event, location, depth of focus, and the travel time residuals.

The event time, magnitude, and duration are obtained from the event record tape. The location is developed from the travel times obtained from the event record tape and is expected to be much less accurate than locations subsequently available from more than one seismic station. The depth of focus determination depends upon the ability to identify on arrival time for the surface-reflected P wave. The travel time residuals are the differences between the actual and expected (steered) arrival times and will generally be available only for relatively strong phases and events, for which an arrival time can be identified.

After each event a seismic bulletin will be prepared and will contain all the following information that is available:

> Time of event
> Magnitude of event
> Duration of event
> Location of event
> Depth of focus
> Phases received
> Region and remarks

2.2.2.2 System Log

A System Log is recommended to provide a status report and a record of the system operation. Array performance, most recent calibration, and input data status are pertinent. Processor status, diagnostic result, an event record and bulletin transmission are output items of interest. Of additional importance are the operator functions and a record of program entries and control executions necessary to sustain system operation.

Section 3

SYSTEM DATA FLOW

Functional system operation can be considered in terms of a systematic data flow of detection, event, and other processing functions. The first two functions can be identified in flow chart terminology by initially considering the processing algorithms depicted in Figure 3-1.

The array signal processing has been divided into five functional algorithms which can be implemented as required, namely:

Recursive filter

Convolution filter

Beam form

Rectify and integrate

Threshold

Using certain appropriate combinations of the algorithms, a large number of linear signal processing techniques may be generated.

A specific set, illustrated in Figure 3-2 has been configured for LASA. From this set, the system data flow has been partitioned into detection and event processing.

3.1 DETECTION PROCESSING

The Detection Processor employs two-step, conventional beam forming to steer the array. In step 1, unfiltered inputs from each subarray are delayed and summed to produce subarray beams (BF-A1). After recursive filtering (FIL-A2), the subarray beams are combined in the second step (BF-A2) to form LASA beams. The time delays used for detection beam forming are generated a priori.

ALGORITHMS

RECURSIVE FILTER ORDER P

$$g_{ij}(n\Delta T) \;=\; b_{oij}f_i(n\Delta T) \;-\; \sum_{p=1}^{P} \{ a_{pij}g_{ij}[(n-p)\Delta T] \;-\; b_{pij}f_i[(n-p)\Delta T]\}$$

CONVOLUTION FILTER ORDER M

$$g_{ij}(n\Delta T) \;=\; \sum_{m=0}^{M} c_{mij}f_i[(n-m)\Delta T]$$

BEAM FORM

$$B_j(n\Delta T) \;=\; \sum_{i=1}^{I} g_{ij}(n\Delta T - \tau_{ij})$$

f_i	– ith Input
g_j	– jth Output
P	– Recursive Filter Order
M	– Convolution Filter Order
n	– Running Time Index
ΔT	– Sampling Time
a	– Filter Coefficient
b	– Filter Coefficient
c	– Filter Coefficient
τ	– Time Delay
d	– Threshold
B_j	– jth Beam Output
$\bar{a}$	– Binary Integration Constant
T_j	– jth Threshold Output

RECTIFY AND INTEGRATE

$$\bar{B}_j(n\Delta T) \;=\; 2^{\bar{a}} \{|B_j(n\Delta T)| \;-\; \bar{B}_j[(n-1)\Delta T]\} \;+\; \bar{B}_j[(n-1)\Delta T]$$

THRESHOLD

$$T_j(n\Delta T) \;=\; \bar{B}_j(n\Delta T) - d_j\bar{\bar{B}}_j(n\Delta T)$$

BEAM FORMING TYPE	RECURSIVE COEFFICIENTS	CONVOLUTION COEFFICIENTS
CONVENTIONAL	0	0
WEIGHTED	I	I
CALIBRATED	J	J
WEIGHT/CAL.	IJ	IJ
OPTIMUM	(2P+1)IJ	(M+1)IJ

Figure 3-1. Algorithms

3-3

(21)25

(SA)S → FIL-A1 ① → (SA)S → BF-A1 → (SA)DSAB → FIL-A2 ② → DSAB(SA) → BF-A2 → DLB → RI-A → T-A → T

B̄

L

B̿

SEISM

WHEN EVENT OCCURS

DETECTION PROCESSING
- -
EVENT PROCESSING

(21)25

EVENT → (21)24 → FIL-B1 → (21)24 → BF-B1 → (21)1 → PICK → FIL-B2 → (1)21 → BF-B2 → ELB → RI-B → T-B → T

B̄

L

B̿

(21)1   C

NOTES:
1. FIL-A1 IS ORDER ZERO AND UNITY COEF.
2. FIL-A2 IS ORDER SIX.

CHANNEL A VALUES				
SA	S	DSAB	DLB	ELB
9	19	4		
13	24	6		
17	25		0 TO 1000	0 TO 300
21				

WHEN S=25, CHANNEL C IS
OMITTED AND CHANNEL B
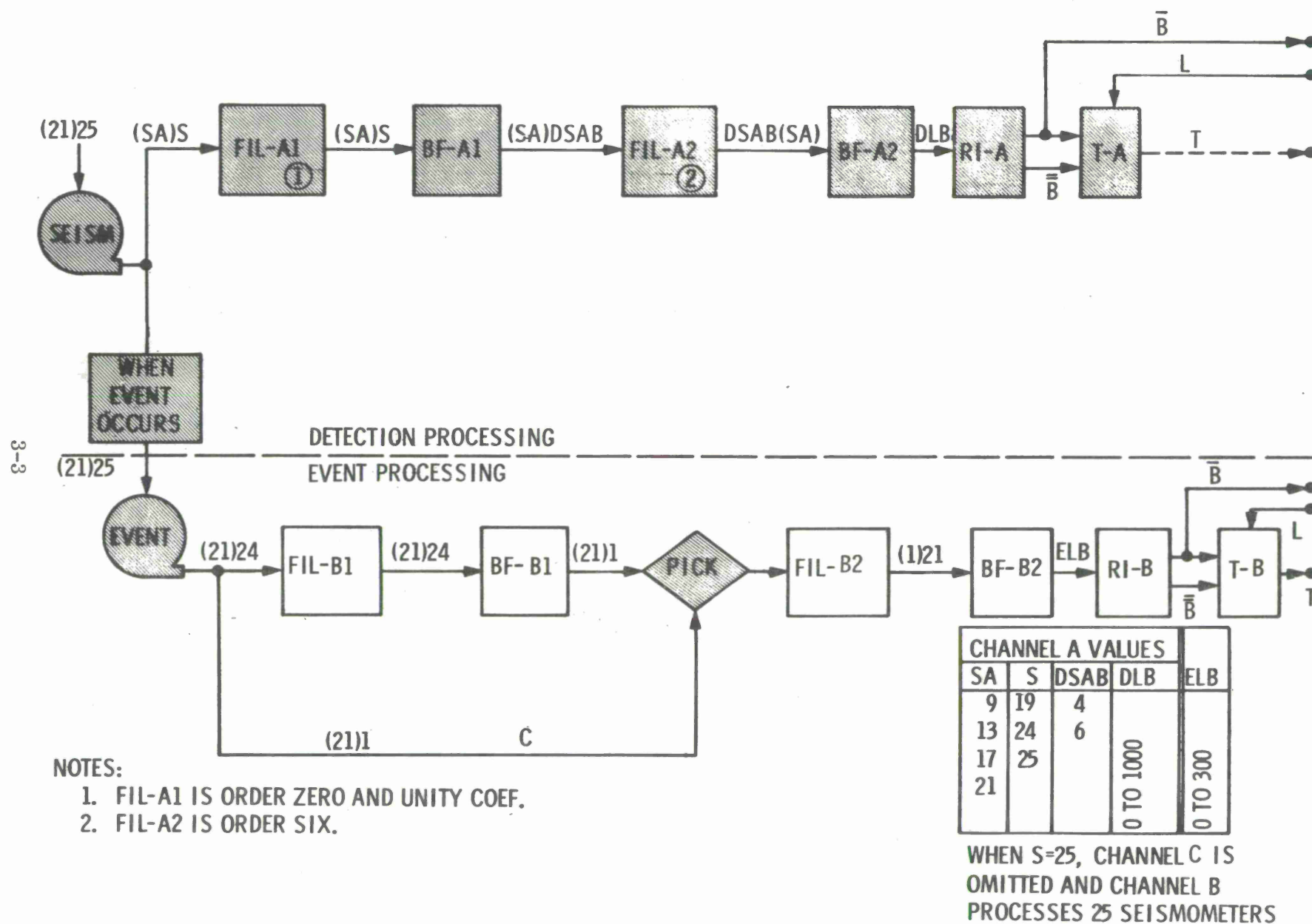PROCESSES 25 SEISMOMETERS

Figure 3-2. Functional Flow Diagram

The Detection Processor program contains a digital filter between the two beam forming steps. This filter is used to limit the signal to the detection frequency range of interest and can be instrumented in either the recursive or convolution form. The type and order of the filter is general; high pass, low pass, band pass, and band rejection filters can be used. The process of changing filter type, kind, and order consists merely of changing coefficients and indices.

With reference to Figure 3-2, FIL-A1 is the filter that would be employed to instrument optimum subarray detection processing. It is also general in formulation and can be configured in either the recursive or convolution form.

To interpret the detection LASA beams, the Detection Processor contains a routine to check these beams against preset threshold levels. To establish the threshold, two integration channels are employed. In the first, the time constant is small, giving short-term smoothing of the signal. In the second, the time constant is large, giving a reasonable long term average noise.

When the ratio of the outputs of these channels exceeds the threshold for a prescribed number of successive samples, a detection has been made. When an event is detected, the present value of the long time constant channel is employed as the threshold for the duration of the event. It serves as an initial condition when the event is terminated.

3.2 EVENT PROCESSING

Within this section, the functions of the Event Processor are discussed; namely event beam forming, beam selection and bulletin generation.

3.2.1 Event Beam Processing

The Functional Flow Diagram (Figure 3-2) shows two possible processing options once an event has been detected. The choice of options is determined by the magnitude of the detected event.

3-4

Normal event processing is shown in Channel B. This is used for events of small magnitude. The processing used in Channel B may be of any type and the filters need not be of the same type.

The first filter (FIL-B1) and beam former (BF-B1) constitute the event subarray processing step. This step forms one subarray beam with its center focused along the center line of the detection LASA beam which indicated the event. The second filter (FIL-B2) and beam former (BF-B2) pair is the event LASA processing step. Here each subarray beam from the first step is filtered and combined to form event LASA beams. These are the beams which, after rectifying/integrating (RI-B), are used for event location.

When the system is saturated by a large event, Channel C is used. The "padded" seismometer arrival times are measured and recorded. This data is passed to the Least Squares Plane Wavefront Program which computes delays for forming event LASA beams. The seismometer inputs are then used directly in the event LASA processing step.

3.2.2 Event Beam Selection

The selection of a single event LASA beam to best describe the event is under investigation. As indicated in Section 2.2.2, at this time the preferred manual beam selection instrumentation is expected to be an intensity modulated CRT type display device.

The display would need the capability to assign to each event LASA beam considered, a unique, addressable position or area on the face of the scope. The resolution must be such that the contours of interest can be easily identified. The magnitude of each beam contribution would be proportional to intensity. It is hoped that the display would yield a pattern similar to the Beam Pattern Contours In Wave Number Space depicted in Figure A-2 of Appendix A.

Beam selection then becomes a process which involves the display of the rectified-integrated event LASA beams formed for each sampling period through-out the recorded duration of the event. The operator, after monitoring the beam display, selects the beam indicated by the area of highest intensity as the event

LASA beam which best describes the event. Due consideration must be given to the presence of side lobes in the selection since they will also be present near the area of highest intensity on the face of the display. The operator will have the capability to instruct the processor to repeat the entire display function. Once the beam has been selected and the processor informed, the beam values for the duration of the events would be recorded on magnetic tape and plotter. It is anticipated that the above procedure will give way to an automated technique for routine event processing. However, such a display will prove useful in testing and experimentation and may become a primary monitoring instrument.

3.2.3 Seismic Bulletin

A seismic bulletin containing available information on time of event, location, magnitude, duration, depth of focus, phases and regions, and remarks would be generated based upon the analysis of the event LASA beams. Dissemination of this bulletin to interested members of the seismic community could be accomplished via common carrier communications.

3.3 OTHER PROCESSING

There are several other processing functions required in the implementation of the system. These functions are implemented throughout the system configuration. Some of these additional functions will be performed in the Event Processor - namely the seismometer calibration analysis, and the time delay calculations. However, the optimum filter coefficient calculation function due to its size and complexity, would be implemented in the Auxiliary Processor. System diagnostic routines would be exercised in each of the processors as discussed in the following paragraphs.

3.3.1 Seismometer Calibration

A calibration signal of known specifications is currently introduced to the LASA system of seismometers, one subarray at a time. To make use of a

seismometer calibration, the system must be capable of the following:

Identification of a calibration signal.

Analysis of the calibration data.

Application of the results of the calibration analysis to the individual seismometers.

The array system currently indicates the introduction of the calibration signal through the telemetry word included in each subarray's outputs. The presence of the appropriate bits in a subarray's telemetry word indicates that the next sample from that subarray will contain calibration signals. This prepares the system for the calibration signal, making identification possible. Since the system knows the specifications of the calibration signal, the response of the seismometers to this signal provides the basis for the analysis. The application of the results of the calibration analysis to the individual seismometers can be accomplished by combining the calibration coefficients with associated filter coefficients.

In conventional processing it is probably not necessary to apply calibration data to the detection function, however, for event processing purposes it may be necessary. If so, the coefficients of the filter through which the seismometer data passes for event processing would be adjusted to reflect the application of the calibration coefficients. In any event, the determination of an inoperative instrument can be made and its signal data subsequently discarded.

3.3.2 Time Delay Calculations

The event subarray beam corresponding to a detected event will be formed for each subarray by assuming that the plane wavefront enters the array at a velocity and azimuth corresponding to the center line of the detection LASA beam on which the detection has occurred. A neighborhood of this center line will be filled with high resolution event LASA beams. These will be formed by adding linear wavefront corrections to the delays corresponding to the detection LASA beam center line.

Alignment of the event subarray beam along the detection beam centerline
allows the total beam loss of 3 & B to be assumed by each event LASA beam in
the cluster; a reduction of event LASA beam requirements is thus realized.
Both of these processes are described in Appendix D.

3.3.3 Optimum Coefficient Calculations

The filter coefficients employed in optimum processing represent the single
largest processor burden. The mathematics of this process as well as means
for estimating its execution time are presented in Appendix E.

If possible it would be preferable to continually provide a set of filter coef-
ficients or if not, at least to provide coefficients for each event processed. To
further identify this requirement would necessitate knowing or predicting the
event rate or the rate at which processing in an optimum manner degrades as a
function of the age of filter coefficients. Execution time, however, is dependent
upon the particular machine selected for this function. If the event rate criterion
is used, then the assumption that coefficients are required once every 30 minutes
seems appropriate.

3.3.4 System Diagnostics

System diagnostics should be provided on two levels. First, a dynamic
diagnostic capability, exercised during normal system operation, should be
designed to indicate possible system malfunction. Second, a static system and
hardware diagnostic capability, exercised when a processor is not operational,
should be developed for regular system maintenance as well as fault condition
isolation.

The diagnostic functions should be designed to test all system functions at
both a programming and hardware level. It should also be accomplished at the
individual processor level as well as the total processing system level.

A design goal of the dynamic diagnostic function should be to hold its execution time to within a small portion of the sample period. In this manner system performance would not be affected and a per sample diagnostic check would be provided. Since a processor undergoing maintenance would not be operational, the static diagnostic could therefore be considerable more extensive.

3.3.5 Time Delay Edit

It is expected that the beam forming steering delays will in general consist of the sum of two parts, a linear, "plane wave" set of delays, and a set of corrections appropriate to the geographic region within which a particular beam is located.

These local corrections will be obtained from seismic travel time corrections that are available for the particular area prior to operations, and will be continually updated as explained below.

When a strong event with clearly defined arrival times is received at LASA, its travel time corrections will in general be incorporated into the previously existing average corrections existing for the region concerned. If the measured times for a strong event should differ substantially from the previous average, it will be necessary to study the possible causes for such a deviation. It is at least conceivable that more than one beam, or more than one set of travel times, might have to be focused at a single "location."

In most cases it is expected that the variability of the corrections in a geographic area of reasonable size will be sufficiently small as to avoid this difficulty. In this case, the new average corrections resulting from the incorporation of a strong event should be but slightly different from the previous steering delays.

Section 4

OPERATIONAL AND MAINTENANCE CONSIDERATIONS

Within this section the processing equipment configuration, and operator functions and requirements are discussed relative to system design.

4.1 PROCESSING CONFIGURATION

In Section 2 (System Functional Requirements) the functions of the Detection and Event Processors are discussed. It appears desirable from both an operational and maintenance viewpoint to have two machines available — one completely dedicated to detection processing and the other for event processing and system backup.

Since the Event Processor must be able to perform the detection process during Detection Processor failure or regular maintenance periods, the former must have at least the processing capability of the latter. In addition, it must be able to perform any other event calculations required by the system. However, from an operations standpoint, the two machines should be as much alike as possible. It is also desirable that the two machines be completely program compatible. In addition, compatibility at the maintenance level is desirable to reduce the service personnel requirements. These requirements lead one to the conclusion that the two machines should be of the same type.

With two identical machines, complete interchangeability of program and function is possible. The system operational program would monitor the Detection Processor for machine errors and automatically realign the machine assignment in the event of a failure. In addition, pertinent machine error messages would be generated to assist maintenance procedures when a failure occurs. The same realignment of function can be used for normal machine maintenance operations, allowing virtually uninterrupted detection processing.

Since the Detection and Event Processors have the same configuration, it is reasonable to require that the input and output units have similar redundancy capabilities. When this is done, I/O unit maintenance can proceed on a regular basis, with the system using alternate units until the normal ones are returned to operation.

In addition to the Detection and Event Processors, an Auxiliary Processor is considered. This computer, although not directly program compatible with the other two, would be oriented towards scientific calculations. It could be used very effectively for background scientific programming as well as optimum coefficient calculations. By using direct channel-to-channel connections with the Auxiliary Processor, the entire processing of an event can proceed automatically with little or no operator intervention.

4.2 OPERATOR FUNCTION

In general, it would be desirable to minimize operator intervention. Consider the following operator functions as typical requirements:

System monitor

Maintenance operations

Selection of the event LASA beam

Magnetic tape functions

These functions will be addressed in terms of the system console and magnetic tape units.

4.2.1 Console

A system console will enable an operator to monitor system status and to communicate with the system. Although each processor in a multiprocessor environment has some device providing operator-machine communication, a centrally located system console reflecting total system status and providing convenient communication capability appears desirable.

System status can be indicated by a set of status lights reflecting the current operational configuration, functions in progress, error checking, and malfunction analyses. Communication capability should include a set of switches to

4-2

notify the system of pertinent operations information, such as the initiation of regular or fault maintenance operations, notification that a processor is being removed from operation, and directions to the system to include or delete certain optional system functions.

The system console must also provide for the entry of operator information into the system, such as logging information and event LASA beam selection. The logging information would include any messages which are pertinent to the function of the system. The selection of the event LASA beam which best describes the event has been discussed in previous sections. It has been noted that it may ultimately not be an operator function. However, it is initially planned as one, and the operator must be provided with a convenient means to monitor the display and notify the system of the beam selected. This display, then, is best considered as part of the system console.

4.2.2   Magnetic Tape

During the initial operation of the processing system, there will be several magnetic tape units which the operator must service. These tape units include the seismometer data tapes, the event tape, and the event record tape. The possibility exists that it may not be necessary to save seismometer and event tapes. Then the only tape which would require service by the operator would be the event record tape. The system should be configured and the programs developed in such a manner that should the requirements for saving tapes be reduced, then the operator tape servicing function can also be reduced.

The recording of the seismometer tapes could be implemented in such a way that the same physical tapes could remain on their respective drives. This mode of operation would utilize three tape units. The seismometer data would be recorded on the first unit, and then proceed to the second and third units. If an event occurs requiring the transfer of data from the first and/or second tape units, this transfer would be done while the third tape unit was being utilized. When the event tape was completely recorded, the first tape unit would be available because its previously recorded data was transferred to the event tape. The operation could theoretically be accomplished with only two tapes, but the third is needed for system backup.

4-3

It should be noted that there is no requirement for unloading the tapes unless they must be saved. The tapes could simply be rewound by the processor to be in position for subsequent recording.

A similar method could be utilized for the generation of the event tapes. Utilizing two tape drives, the event tape would be generated from the seismometer tape by the Detection Processor, rewound, and then switched logically to the Event Processor for event processing. The second tape unit would be used to generate an event tape for any events which may occur during the processing of the current event. Again, there is no need for an operator to service the tape units unless the event tapes are to be saved.

The operator requirements to service the tape units could then consist of servicing only the event record tape if it were the only tape to be saved. The tapes would, however, be removed periodically as part of the regular maintenance procedures.

4.3 OPERATOR REQUIREMENTS

The above mentioned operational and maintenance considerations are aimed at enhancing system performance as well as reducing operator intervention. This, of course, implies that the system supervisor and monitor routines provide the capability to implement the required operational functions as described. It appears that the multisystem operation as described would require two operators per shift to provide the necessary operational and maintenance functions. One of the two operators must have a total system understanding as well as the necessary training to monitor or perform the beam selection process.

Appendix A

SURVEILLANCE COVERAGE

This Appendix presents the requirements for conventional beam forming to accomplish detection and event processing.

Four types of beams have to be formed simultaneously:

> Detection subarray beams
> Detection LASA beams
> Event subarray beams
> Event LASA beams

SUBARRAY BEAM REQUIREMENTS

The number of subarray beams to be generated is a function of the area to be covered and the signal frequency components to be preserved. For detection, it is believed that a detection frequency at or below 1.5 Hz is optimal. It will be shown that at this frequency, the world, i.e., the entire teleseismic zone between the ranges of 30° and 95° from any given point on the globe, can be covered by six subarray beams with a subarray beam forming loss which nowhere exceeds 1.3 dB. A seventh or vertical subarray beam, looking at the earth's core, may be useful in addition.

This and other possible subarray beam coverages of the teleseismic zone as seen from Montana are summarized in Table A1.

Table A1

SUBARRAY BEAM COVERAGES

Number of Subarray Beams	Coverage
7	World teleseismic region and one vertical beam
6	World teleseismic region
5	World teleseismic: all land areas and seismic zones
4	World teleseismic: all land areas and seismic zones, excluding Pacific Island area.
3	World teleseismic: all land except Pacific Islands, and major part of seismic zones
2	World teleseismic: Europe-Asia-Africa land areas; South America is excluded.

All subarray beams presented in Table A1 were assumed to lose no more than 1.3 dB at 1.5 Hz. If less than full world coverage with 6 subarray beams is desired, some of these subarray beams may be reduced in size to eliminate ocean coverage, and thus the worst subarray beam loss can be decreased below 1.3 dB. This would in turn relax the number of detection beams required.

DETECTION BEAM REQUIREMENTS

Reference is made to Figure 1-2. The curve labeled "World" shows the number of 1.5 Hz detection beams required to cover the teleseismic region with detection beam loss no greater than 1.7 dB. This loss, added to the 1.3 dB worst subarray beam loss, provides a detection loss which is not greater than 3.0 dB at 1.5 Hz. The number of detection beams is shown as a function of the number of subarrays used for detection, going from nine (LASA less three outer rings) through thirteen (LASA less two outer rings), seventeen (LASA less one outer ring) to twenty-one (the full LASA array).

A-2

It is important to note that the indicated 3 dB loss represents the loss caused by a lack of perfect steering, but does not include the loss resulting from failure to utilize the full LASA capability when SA < 21. This additional loss is shown in the "Loss" curves using the dB scale on the right side of the chart.

The two curves, "Land and Seismic Not On Land" and "Land Only" give the corresponding information for less than "World" coverage. The number of subarray beams, appropriate to these two curves, is seen from Table A-1 to be 5 (4 without Pacific Islands) and 4 (3 without Pacific Islands), respectively.

EVENT BEAM REQUIREMENTS

When forming event beams there need be little loss in subarray beam forming, because a subarray beam can be focused directly on or very near to the detected event. Therefore, event beam forming can be permitted a full 3.0 dB loss. The cutoff frequency for event beam forming purposes has been chosen as 3.0 Hz. It is difficult to predict precisely how many event beams might be required. It is reasonable, however, to assume that the number is related to a region of uncertainty surrounding the detection beam upon which a detection has been made.

The two event curves shown in Figure 1-2 are obtained by counting the number of 3.0 Hz, 3.0 dB event beams required to fill, respectively, the 9.0 dB contour of a 1.5 Hz detection beam, and a circle containing this contour. The assumption which has been made here is that the best event beam should be somewhere within the area in which the detection beam loss is no more than 9.0 dB. Even with this seemingly precise definition, the event curves should be regarded only as estimates. The existence of severe side lobes at the 9.0 dB level, not far removed from the main 9.0 dB contour, makes the choice of the areas to be covered somewhat arbitrary, depending on which side lobes are included as part of the region of uncertainty.

ARRAY BEAM PATTERNS

The analysis of detection beam requirements, summarized above, rests on the relationship between the beam patterns of the covering detection beams, and the distribution of areas to be covered in the teleseismic zone. The event beam requirements, in turn, depend on the relationship between event and detection beam patterns. Thus, beam patterns are fundamental to both analyses, and the relevant patterns are presented herein.

Figure A-1 shows beam patterns for the full 21 subarray LASA, along with three reduced arrays in which the outer rings of subarrays have been omitted. The values plotted exhibit, among other things, the loss at that azimuth where the loss is greatest. The figure shows the effect on the LASA beam pattern of removing one to three of the outer rings of subarrays. Note the beam broadening and the side lobe reduction as the number of sub-arrays employed decreases.

Figure A-2 shows dB contours for the same beam patterns. For all four array configurations shown, the contours are given at the 1.7, 6.0, 9.0, and 12.0 dB levels. The 1.7 dB level is used to show the size of detection beams which, with a 1.3 dB subarray loss, give a total 3.0 dB loss. The 6.0, 9.0, and 12.0 dB contours are shown to indicate the possible size of the uncertainty area which must be filled with event beams. The event beams themselves are permitted a 3.0 dB loss because of the assumption of perfect subarray event steering. Since event beams will always be formed from 21 subarrays, the 3.0 dB beam contour is shown only for the full LASA.

INVERSE VELOCITY SPACE COVERAGE

Figure 1-1 shows a map of the world in inverse velocity (u_x, u_y) space with respect to Montana. The azimuth of each point relative to the origin is the true azimuth of the point as seen from Billings, Montana. The distance from the origin is the reciprocal of the horizontal phase velocity of a signal arriving at Billings from that particular range. This representation is, of
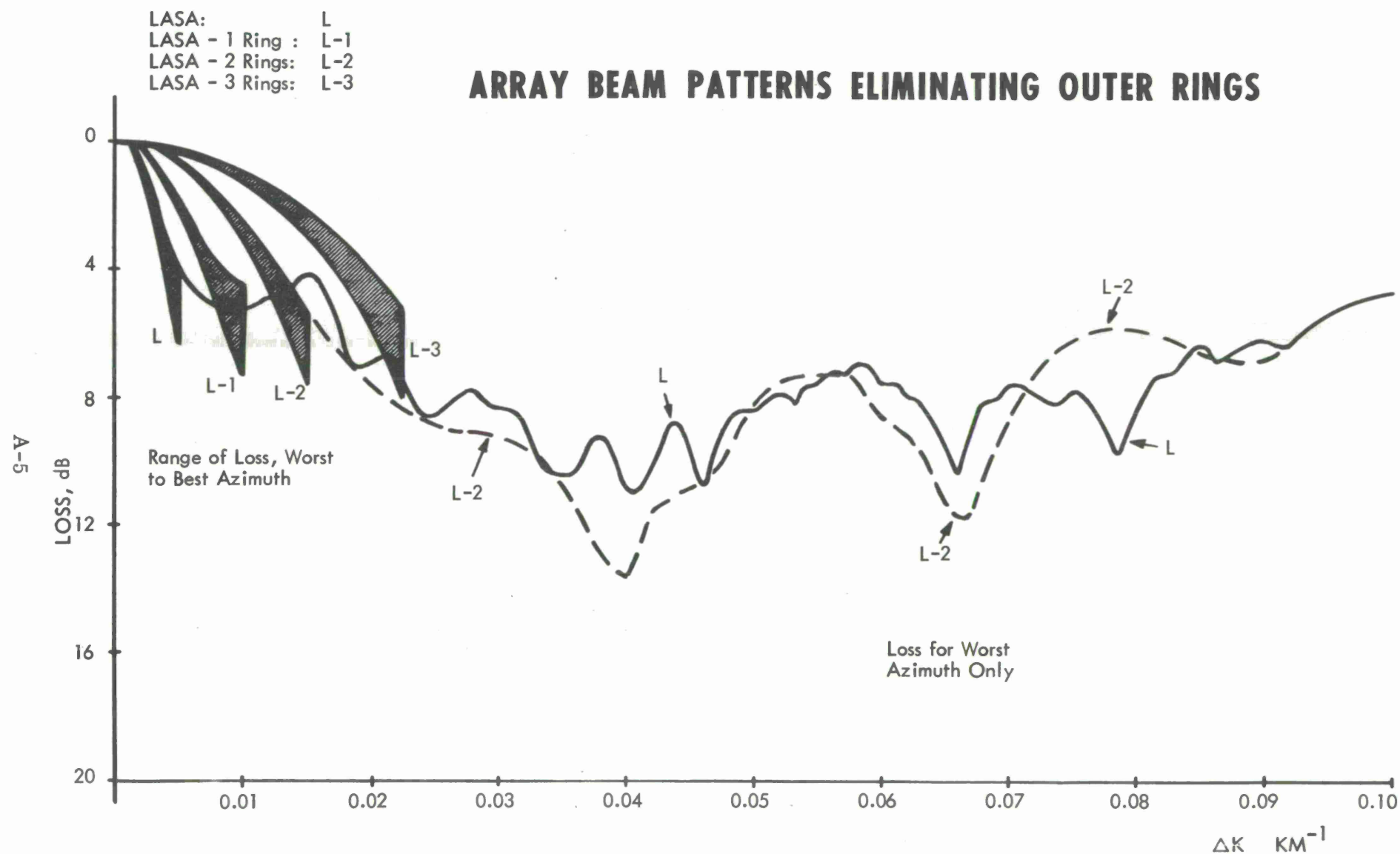
Figure A-1. Array Beam Patterns Eliminating Outer Rings

LASA LESS 3 RINGS
9 SUBARRAYS

LASA LESS 2 RINGS
13 SUBARRAYS

LASA LESS 1 RING
17 SUBARRAYS

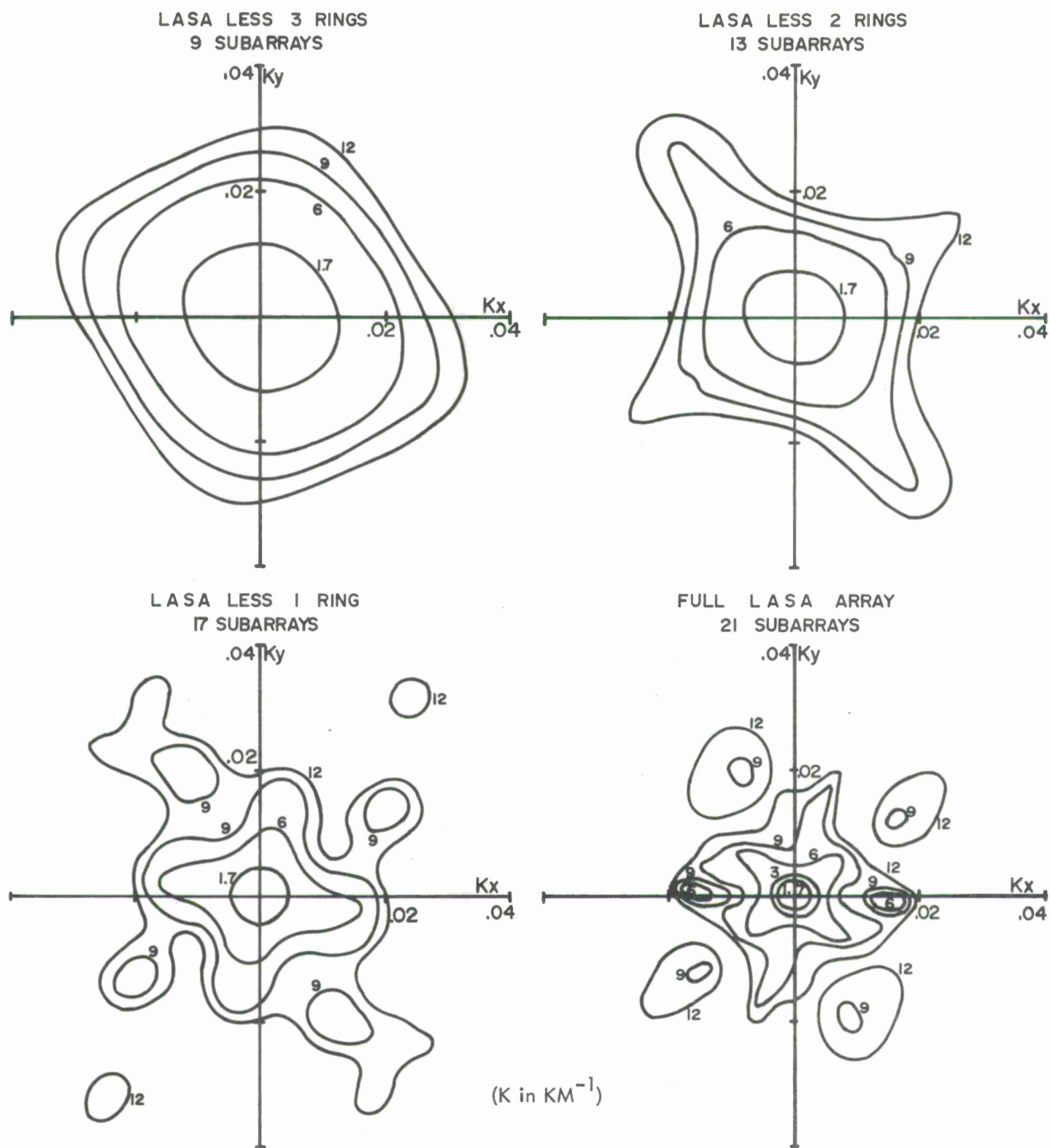FULL LASA ARRAY
21 SUBARRAYS

(K in KM⁻¹)

Figure A-2. Beam Pattern Contours in Wave Number Space

course, frequency-independent (and is equal to a wave number space representation at a frequency of 1.0 Hz). The inserts show the size of typical beams to be used.

The relationship between inverse velocity $u = \sqrt{u_x^2 + u_y^2}$ and range R which has been used in preparing this projection is:

$$R = 13{,}528 - 46{,}116u - 10^6 u^2.$$

This relationship (R in km, u in sec/km) is valid only in the teleseismic zone, about $0.04 \leq u \leq 0.08$ sec/km, where it has been fitted to results of ray traces based on the earth's velocity profile. which in turn is derived from empirical travel time data.

In order for a set of beams to cover a given portion of this u-space map, the area of all the beams should approximate the area of the map portion. As shown in the inserts of Figure 1-1, the 1.7 dB contours of the beams are very nearly circles. We shall assume that they are in fact circles, and that they will most efficiently fill a given large area if the circles are close-packed. In this case, the non-overlapping area covered by each circle of radius c is the area of its inscribed hexagon, or

$$A_{beam} = \frac{3\sqrt{3}}{\pi} c^2 = 2.60c^2.$$

The efficiency of coverage of the close-packed system is seen to be $2.60c^2/\pi c^2 = 83\%$. The radius c of a beam for small ΔK can be obtained by dividing ΔK from the beam patterns (Figure A-2) by the frequency f. If the area to be covered is sufficiently large so that the edge effects may be neglected, then the number of beams required is:

$$N = \frac{A}{2.60c^2}$$

For beams which are relatively large compared to the map topography, it is more accurate to use beam templates, overlay them on the map, and actually count the beams required. Such templates are in preparation for a number of circle sizes, from which an empirical relationship can be derived from the actual beam counts.

To determine requirements for event LASA beams, 3.0 dB event LASA beam contours are fitted into the 9.0 dB detection LASA beam contour. Instead of dividing the size of the covering event beam pattern radius by its frequency, it must be divided by the ratio of its own frequency to that of the detection LASA beam to be covered, i.e., normalized for the frequencies of interest.

Appendix B

COVERAGE VARIATION ANALYSIS

The purpose of this appendix is to discuss briefly the sensitivity of
the beam requirements shown in Figure 1-2 to the assumptions made in
deriving them. By far the most important of these parameters is the
detection frequency which is the upper limit of the signal frequency where
the signal-to-noise ratio peaks. If edge effects are neglected, then the
number of detection beams required to cover a given geographic area is
proportional to the square of the detection frequency. Thus, for example,
the 360 beams required when 17 subarrays are employed to cover land
and seismic areas not on land at the assumed frequency of 1.5 Hz, will
become 160 and 810, respectively, at 1.0 Hz and 2.0 Hz. If edge effects
are considered, then the 160 would be raised 5 or 10 percent because of
the relatively inefficient area coverage of larger beams. By the same
token, the 810 is actually somewhat lower because of more efficient area
coverage.

The number of event beams required, on the other hand, is approxi-
mately proportional to $(f_e/f_d)^2$, where f_e and f_d are, respectively, the
cutoff frequency of the event beam and the detection frequency of the
detection beam. Thus, for example, increasing the frequency of the de-
tection beams would decrease their size, increase their number, but
decrease the number of event beams required to cover one of them.

A second assumption is that the event beams should cover an area of
detection uncertainty, and the 9.0 dB contour of a detection beam was selected
as appropriate. As shown in Figure 1-2, filling a circle circumscribing
this contour somewhat increases the number of event beams required.

Also, if the 6.0 dB or 12.0 dB contour were used instead of the 9.0 dB contour, then the number of event beams would be respectively reduced or increased by about 50 percent.

The effect of a variation in the detection frequency on the required number of detection and event beams is depicted in Figures B-1 and B-2, respectively.
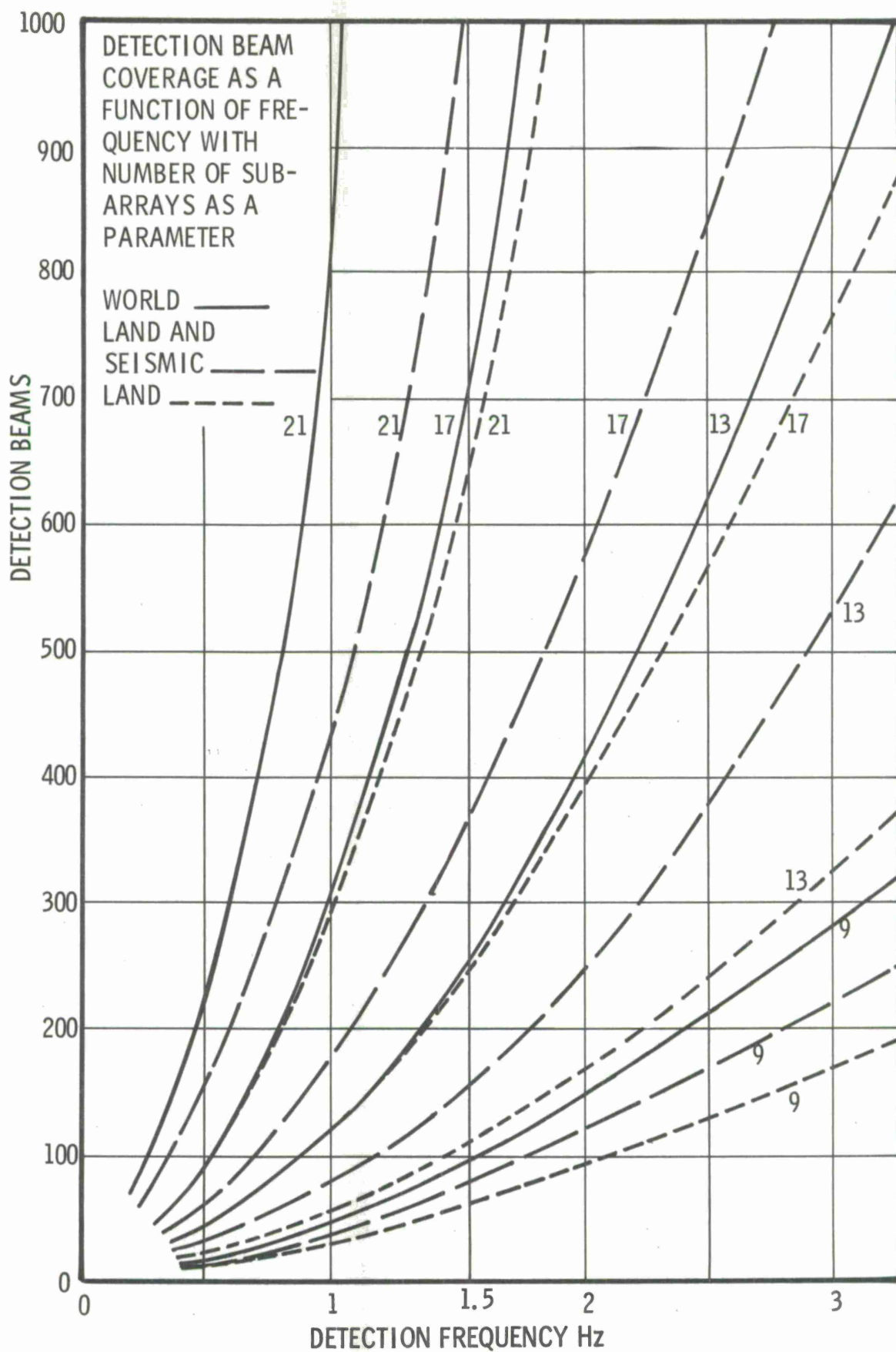
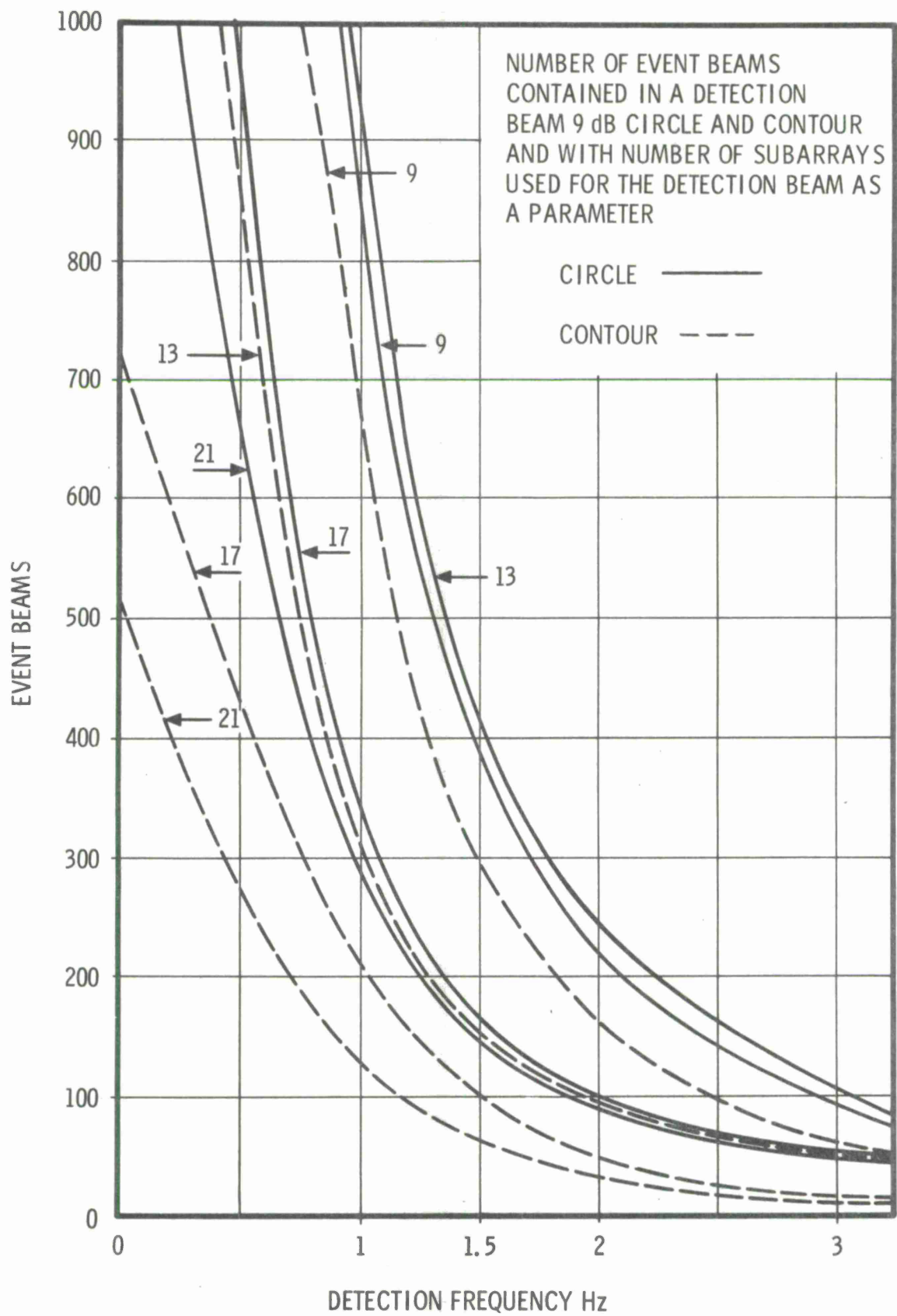Figure B-1. Detection Beam Coverage

Figure B-2. Event Beam Coverage

Appendix C

SPECIFICATIONS FOR SCALING, SEISMOMETER
SENSITIVITY TOLERANCES, SAMPLING RATE
AND QUANTIZATION AND WORDLENGTH

This appendix addresses the data input and the Detection Processor requirements. However, the requirements mentioned below for scaling, seismometer tolerances, and sampling rate will be taken to apply also to event processing. At this time it appears difficult to assess the increase in optimum processing gain which would result from more stringent requirements on these parameters.

Scaling. For each subarray, all seismometer output traces, except one, are transmitted to the signal processor with a wordlength of 13 bits plus sign at a scaling of 0.028 nanometer per bit. The exceptional seismometer for each subarray is so "padded" that it is transmitted at a wordlength of 13 bits plus sign, scaled to 3.584 nanometers per bit. This scaling affords event recording without system saturation for seismic events up to magnitude eight.

In addition, the last (least significant) triplet of bits of the "non-padded" seismometers will be shifted off prior to the output entering the Detection Processor such that the scaling is 0.224 nanometer per bit. In addition, provisions have been made to allow binary scaling changes over the full range of the data word.

Seismometer Tolerances. In the frequency range from 0.5 Hz to 2.0 Hz, the seismometer sensitivities shall be within $\pm$ 35 percent of nominal, while the seismometer phase responses shall be within $\pm$ 30 degrees of nominal. These tolerances will limit to 0.5 dB the loss in processing gain caused by sensitivity and phase response variations among seismometers.

Sampling Rate. Every seismometer output trace shall be transmitted to the signal processor at a rate of ten samples per second.

Postulating a detection center frequency of 1.5 Hz or below, this sampling rate will limit to 0.4 dB the loss in processing gain caused by the quantized implementation of the time delays required for beam forming.

In addition, the sampling rate is sufficiently high to hold to insignificant levels the effects of "folding" high-frequency noise into the frequency region below 2.0 Hz.

Quantization and Wordlength. In the detection processor, 16-bit fixed point arithmetic (15 bits plus sign) will be used, except for filter multiplies and adds which will be performed with double precision for the control of filter round-off error.

The outputs of the "non-padded" seismometers are represented by 15 bits plus sign with a scaling of 0.224 nanometer for the least significant bit. Subarray detection beam outputs before recursive filtering are represented by 15 bits plus sign at a scaling of 0.224/K nanometer for the least significant bit. Here K is the number of seismometer outputs used per subarray beam. After recursive filtering, the subarray detection beam output is shifted right two binary places, for a representation by 15 bits plus sign and a scaling of 0.896/K nanometer for the least significant bit. Event beam outputs, prior to rectification, are represented by 15 bits plus sign, with the least significant bit scaled to 0.896/KN nanometer. Here, N is the number of subarray detection beam outputs used in the LASA beam formation.

With $K = 24$ and $N = 21$, allowing an extra one-bit margin to prevent overflow within the processor, no instrument saturation or processor overflow will occur for seismic events with amplitudes up to 52 nanometers. Events above 52 nanometers are readily detected and processed by means of the outputs of the "padded" seismometers. Thus there will indeed be no saturation or overflow problems for events up to magnitude eight (amplitudes up to 2.8×10^4 nanometers).

For the scaling described above, assuming a noise level of about 5 nanometers in a seismometer output and a processing gain of about 30 dB, the quantization errors will cause an acceptable loss in processing gain (less than 0.5 dB) provided care is exercised in the implementation of the recursive filters for the subarray beam outputs. Because of the high-pass characteristics required for such a filter, excessive round-off error can possibly be generated when the filter is implemented directly as a band-pass filter operating at a sampling rate of 10 samples per second. In that case, round-off error build-up can be controlled by an implementation of a low-pass filter operating at 10 samples per second followed by a high-pass filter operating at 5 samples per second.

Appendix D

TIME DELAY CALCULATION

First, the time delays for an event subarray beam must be calculated for each subarray. It is assumed that a detection has been accomplished and a detection beam selected as the best one. The location of the source is approximated by the location of the centerline of that detection beam. If (u_{xc}, u_{yc}) is that centerline location in inverse-velocity space, then the plane wave steering delays for any subarray consisting of a set of sensors, the kth of which has location (x_k, y_k), is

$$\Delta t_{kc} = - (x_k u_{xc} + y_k u_{yc}).$$

Because of the relatively small size of the subarrays compared to expected wave front curvatures, all subarrays both in detection and event processing can be steered, with negligible loss, for plane wave fronts. Therefore, the above equation will be used for the event subarray beam.

To generate a set of event beams to cover a given detection beam contour, let it again be assumed that a detection has been accomplished on a detection beam whose centerline lies at $\bar{u}_c = (u_{xc}, u_{yc})$ in inverse-velocity space, and whose steering delays are t_{kc}, where the index k now denotes the kth subarray. A set of event beams can then be generated by using the delays corresponding to this detection beam center, modified by linear variations corresponding to deviations from the center line. The delay at the kth subarray, whose center position is taken as (x_k, y_k) for a beam aimed at the location (u_x, u_y), can then be expressed as follows:

$$\Delta t_k = \Delta t_{kc} - \left[(u_x - u_{xc}) x_k + (u_y - u_{yc}) y_k \right].$$

A set of neighboring beams related to the centerline is then defined
by causing (u_x, u_y) to increment so as to form a close-packed system of
beams, and limiting the neighborhood by prescribing that

$$\left[(u_x - u_{xc})^2 + (u_y - u_{yc})^2 \right] \leq R^2 ,$$

where R is the radius of the circle of the selected area of detection beam
uncertainty. A close-packed system may be defined by incrementing
(u_x, u_y) according to the rules

$$u_x = u_{xc} + r \sqrt{3} (m + 0.5 \, n),$$

$$u_y = u_{yc} + 1.5 \, nr,$$

where r is the 3.0 dB radius of an event beam in (u_x, u_y) space, and m and
n are integers.

Appendix E

CALCULATION OF FILTER COEFFICIENTS

INTRODUCTION

This calculation consists of two parts. In the first part, the cross spectral matrix of the noise in the output traces of K seismometers is calculated for a number of frequencies. In the second part, these cross spectral matrices are utilized to compute the time domain coefficients of the desired optimum filters.

CALCULATION OF THE CROSS SPECTRAL MATRIX

Consider a "block" of K seismometer traces each consisting of A samples (A is taken to be a power of two):

$$x_k(a); \ k = 1, \ ---, \ K; \ a = -\frac{A}{2} , \ ---, \ -1, 1, \ --- \ , \frac{A}{2} , \tag{1}$$

where k is the seismometer index and a is the sampling index. It has been assumed that these traces have already been delayed with respect to each other in order to achieve steering in a predetermined direction.

Using the Cooley-Tukey method, the Fourier transforms are calculated:

$$\hat{x}_k(a) = \sum_{b = -\frac{A}{2}}^{\frac{A}{2}} e^{-2\pi i a b /A} \, x_k(b); \ a = 1, \ ---, \frac{A}{2} , \tag{2}$$

(since $\hat{x}_k(a)$ and $\hat{x}_k(-a)$ are complex conjugates, only positive values of the frequency a need be considered). From (2) we compute $\frac{A}{2M}$ Hermitean matrices (M is a power of two so chosen that the filter point spacing will be MT, with T denoting the sampling interval of the seismometer traces):

$$\psi_{k,\ell}(a) = \hat{x}_k(a)\hat{x}_\ell(a)^*; \quad k,\ell = 1,---,K; \; a = 1 ---,\frac{A}{2M} \tag{3}$$

Here $(\ )^*$ denotes the complex conjugate of $(\ )$. This procedure is performed for N successive "blocks" and the cross spectral matrix $\phi_{k\ell}(a)$ is obtained by averaging:

$$\phi_{k\ell}(a) = \frac{1}{N} \sum_n \psi_{k,\ell}^{(n)}(a) \; ; k,\ell = 1, --- , K; \; a = 1,---,\frac{A}{2M} \tag{4}$$

where the symbol "n" is the "block" index, running from 1 to N.

CALCULATION OF THE TIME DOMAIN COEFFICIENTS

For each frequency $a = 1, ---, A/2M$ the following K linear equations:

$$\sum_{\ell=1}^{K} \phi_{k,\ell}(a) \, \hat{h}_\ell(a) = 1; \; k = 1, ---,K \tag{5}$$

are solved for the unknowns $\hat{h}_\ell(a)$. These equations and the unknowns are complex-valued. The set of equations (5) is equivalent to a set of 2K real-valued equations with 2K real-valued unknowns. Next define

$$\hat{h}_k(-a) = \hat{h}_k(a)^* \tag{6}$$

and the time-domain filter coefficients (k = 1, ---, K)

$$h_k(Ma); \ a = -\frac{A}{2M}, \ ---, \ -1, \ 1, \ ---, \frac{A}{2M} \tag{7}$$

are obtained by computing the Fourier transforms of the K sequences

$$\hat{h}_k(a); \ k = 1, ---, K; \ a = -\frac{A}{2M}, \ ---, -1, \ 1, \ ---, \frac{A}{2M} \ . \tag{8}$$

Note that the time-domain filter coefficients (7) are real-valued as a consequence of formula (6).

GENERAL COMMENTS

Each of the K time domain filters (7) has a duration of AT seconds and consists of A/M filter points, spaced MT seconds apart. The filter duration should be so chosen that both signal and noise spectrum will vary smoothly and predictably in any frequency interval of length $\Delta f = 1/AT$ Hz. The filter point spacing MT must satisfy the requirement that most of the coherent signal energy will be below $f_{max} = 1/2$ MT Hz.

After the digital filters have been applied to the K seismometer traces, addition of the K resulting outputs yield the optimum subarray beam output. This trace, if desired, can be filtered with a low-pass filter cutting off at f_{max}. As an example assume T = 0.1 sec, corresponding to sampling at 10 samples per second, assume $\Delta f = 0.16$ Hz and $f_{max} = 2.5$ Hz. This leads to A = 64 and M = 2, i.e., to a filter length of 6.4 sec.and to 32 filter points per filter. Because of the rapid change of the noise spectrum at low frequencies, the choice of 0.16 Hz for Δf may be too large, i.e., the filter duration of 6.4 seconds may be too short. In order to achieve acceptable accuracy for the cross-spectral matrix (4), the value of N should probably be on the order of about 50 to 100.

The execution time for the calculation of the K filters (7) can be calculated approximately by noting that the computation of the cross-spectral matrices (4) requires about:

$$2NKA \ \log_2 A \ + \ \frac{K^2 NA}{M} \tag{9}$$

E-3

real multiplies, while the calculation of the KA/M coefficients (7) necessitates approximately

$$\frac{4}{3} \frac{K^3 A}{M} + 2K \frac{A}{M} \log_2 (\frac{A}{M})$$ (10)

real multiplies.

It is finally noted that the traces (1) have been assumed delayed with respect to each other in order to achieve steering in a predetermined direction. When this procedure is omitted, the right-hand sides of the equations (5) must be modified to read

$$\exp (2\pi i a n_k T/A); \ k = 1, \text{---}, K$$ (11)

where $n_k T$ is the delay which would otherwise have been applied to the kth seismometer trace.

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13. ABSTRACT

This rpt sets forth a functional description of a LASA Signal Processing System. The system parameters have been chosen by taking advantage of important system tradeoffs to reduce the hardware necessary to implement the known operating requirements. The system discussed herein is configured to allow considerable experimentation. Generalized processing techniques and system partitioning have been employed to permit growth and change on the basis of experimental results. On the other hand, certain desired operational system functions and performance objectives can at this time be identified. These have been taken into account so that immediate advantage can be taken of existing array equipments and signal processing technology.

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